Compression Springs

SPRINGS & THINGS
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General Data

A compression spring is an open-coil helical spring that offers resistance to a compressive force applied axially. Compression springs are usually coiled as a constant-diameter cylinder. Other common forms of compression springs—such as conical, concave (barrel), convex (hourglass), or various combinations of these—are used as required by the application. While square, rectangular, or special-section wire may have to be specified, round wire is predominant in compression springs because it is readily available and adaptable to standard coiler tooling.

The illustration on page 17 is recommended as a guide in specifying compression springs. The functional design characteristics of the spring should be given as mandatory specifications. Secondary characteristics, which may well be useful for reference, should be identified as advisory data. This practice controls the essential requirements, while providing as much design flexibility as possible to the spring manufacturer in meeting these requirements.

Compression springs should be stress-relieved to remove residual forming stresses produced by the coiling operation. Depending on design and space limitations, compression springs may be categorized according to stress level as follows:

1. Springs which can be compressed solid without permanent set, so that an extra operation for removing set is not needed. These springs are designed with torsional stress levels when compressed solid that do not exceed about 40 percent of the minimum tensile strength of the material.
2. Springs which can be compressed solid without further permanent set after set has initially been removed. These may be pre-set by the spring manufacturer as an added operation, or they may be pre-set later by the user prior to or during the assembly operation. These are springs designed with torsional stress levels when compressed solid that usually do not exceed 60 percent of the minimum tensile strength of the material.
3. Springs which cannot be compressed solid without some further permanent set taking place because set cannot be completely removed in advance. These springs involve torsional stress levels which exceed 60 percent of the minimum tensile strength of the material. The spring manufacturer will usually advise the user of the maximum allowable spring deflection without set whenever springs are specified in this category.

In designing compression springs the space allotted governs the dimensional limits of a spring with regard to allowable solid height and outside and inside diameters. These dimensional limits, together with the load and deflection requirements, determine the stress level. It is extremely important to consider carefully the space allotted to insure that the spring will function properly to begin with, thereby avoiding costly design changes.

Solid Height

The solid height of a compression spring is defined as the length of the spring when under sufficient load to bring all coils into contact with the adjacent coils and additional load causes no further deflection. Solid height should be specified by the user as a maximum, with the actual number of coils in the spring to be determined by the spring manufacturer.

As square or rectangular wire is coiled, the wire cross-section deforms slightly into a keystone or trapezoidal shape, which increases the solid height considerably. This dimensional change is a function of the spring index and the thickness of the material. It may be determined approximately by the following formula:

$$t' = 0.48t\left(\frac{\text{O.D.}}{\text{D}} + 1\right)$$

where t' equals new thickness of inner edge (in the axial direction) after coiling and t equals thickness before coiling. When calculating maximum solid height, allowance must be made for all the factors which apply, such as material, finish, and manufacturing tolerances.

How to Determine Rate

Rate, which is the change in load per unit deflection, may be determined by the following procedure:

1. Deflect spring to approximately 20 percent of available deflection and measure load (P_1) and spring length (L_1).
2. Deflect spring not more than 80 percent of available deflection and measure load (P_2) and spring length (L_2). Be certain that no coils (other than closed ends) are touching at L_2.
3. Calculate rate (R) lb./in. (N/mm)

$$R = (P_2 - P_1)/(L_1 - L_2)$$

Spring Ends

There are four basic types of compression spring ends, as shown on page 17. The particular type of ends specified affect the pitch, solid height, total coils, free length, and seating characteristics of the spring. The type of ends and the pitch determine to a large extent the amount of tangling that occurs when the springs are handled in bulk.

The table below gives formulas for calculating dimensional characteristics for various types of ends on compression springs. In applying the given data to solid height, it should be remembered that there are several factors which the formulas do not consider. The actual solid height may not be the same as the calculated value due to improper seating of coils, normal variation in wire size, and electroplating, which adds appreciably to the wire size.

Table 1.
FORMULAS FOR DIMENSIONAL CHARACTERISTICS

Spring Characteristic	Type of Ends			
	Open	Open & Ground	Closed	Closed & Ground
Pitch (p)	$\frac{L - d}{n_a}$	$\frac{L}{n_a}$	$\frac{L - 3d}{n_a}$	$\frac{L - 2d}{n_a}$
Solid Height (H)	$d(N_t + 1)$	$d \times N_t$	$d(N_t + 1)$	$d \times N_t$
Total Coils (N_t)	n_a	$n_a + 1$	$n_a + 2$	$n_a + 2$
Free Length (L)	$(p \times n_a) + d$	$p \times n_a$	$(p \times n_a) + 3d$	$(p \times n_a) + 2d$

End Coil Effects

A compression spring cannot be closed and ground so consistently that its ends will always be square (in parallel planes at right angles to its axis). In addition, the helix angles adjacent to the end coils will not have uniform configuration and closing tension, and these springs cannot be coiled so accurately as to permit all coils to close out simultaneously under load. As a result of these end coil effects, the spring rate tends to lag over the initial 20 percent of the deflection range, often being considerably less than calculated. As the ends seat during the first stage of deflection, the spring rate rises to the calculated value. In contrast, the spring rate for the final 20 percent of the deflection range tends to increase as coils progressively close.

The spring rate over the central 60 percent of the deflection range is essentially linear for constant pitch springs. If possible, critical loads and rates should be specified within this range, which can be increased to about 80 percent of total deflection by special production techniques. However, these techniques add to manufacturing cost and are often unwarranted.

Squareness of Ends, Grinding, and Degree of Bearing

The squareness of compression spring ends influences the manner in which the axial force produced by the spring can be transferred to adjacent parts in a mechanism. There are some types of applications where open ends may be entirely suitable. However, when space permits, closed ends afford a greater degree of squareness and reduce the possibility of tangling with little increase in cost. With closed ends, the degree of squareness depends on the relationship of the wire diameter (d) and the mean coil diameter (D). Unground springs with indexes (D/d) that are low have less squareness, while unground, high-index springs have more squareness. Compression springs with closed ends can often perform well without grinding, particularly in wire sizes smaller than 0.020 in. (0.51 mm) or spring indexes exceeding 12.

Many applications require grinding the ends in order to provide greater control over squareness. Among these are applications in which (1) high-duty springs are specified, (2) unusually close tolerances on load or rate are needed, (3) solid height must be minimized, (4) accurate seating and uniform bearing pressures are required, and (5) a tendency toward buckling must be reduced.

Springs with closed and ground ends which have a free length more than four times the mean diameter ($L/D > 4$) can buckle in some applications, depending on the ratio of deflection to free length. Mounting the spring in a tube, over a rod and/or on parallel fixed plates are methods commonly used to reduce the tendency for buckling. Unground springs are more susceptible to buckling than are ground springs and may buckle at (L/D) ratios less than 4.

Since springs are flexible and external forces tend to tilt the ends, grinding to extreme squareness is difficult. Squareness of 3° can normally be maintained by standard manufacturing methods on ground springs. Tolerances closer than 3° require special techniques and added operations, which increase manufacturing costs.

A spring may be specified for grinding square in the unloaded condition or square under load, but not in both conditions with any degree of accuracy. When squareness at a specific load or height is required, it should be specified.

Well-proportioned, high-quality compression springs which are specified with closed and ground ends should have the spring wire at the ends uniformly taper from the full wire diameter to the tip. A slight gap, which occasionally opens during grinding, is permissible between the closed end coil and the adjacent coil. The bearing surface provided by grinding should extend over a minimum of 240° of the end coils. Results will vary considerably from these nominal attainable values with springs in smaller wire sizes or with higher indexes. In general, it is impractical to adhere to a general rule regarding "degree of bearing," since process capabilities depend so much on the individual configuration of the spring.

Design Method: Load

The design method for helical compression springs is mainly a process of manipulating the formulas for spring rate and torsional stress (see p. 8).

How these formulas are applied depends on what spring characteristics the engineer needs to calculate. These include 1) those spring characteristics which are not fixed by application requirements but must be recorded to specify a complete spring and 2) those characteristics which are fixed by the application and are used to determine whether the spring being designed fulfills the requirements. The logic of the design method (not the detailed steps involved in reaching a solution) follows. The examples in this section involve the same design logic and can be solved entirely with the data given here.

The most common specifications given in designing a compression spring are one load and a deflection from the free position or two loads and a deflection between these loads, dimensions of available space, types of ends, and any factors which govern selection of the spring material. The basic method is to design the spring for maximum economy (of space, weight, and dollars) by calculating the wire diameter (d) corresponding to the maximum allowable stress in formula 2 and then using formula 1 to determine the number of active coils (n_a).

To determine d the designer solves formula 2 using trial values for stress (S_t), mean diameter (D), and load (P) or load at solid (Ps). Unless the mean diameter (D) is given, the designer makes D = OD to get a trial value of d. The trial value of torsional stress (S_t) in formula 2 is determined by multiplying a trial value of minimum tensile strength (not critical, select values from Table 1, page 7, or from tables on pages 44 to 46) by the appropriate percentage from the materials table on pages 41 and 42. Since this trial value of stress is usually the maximum allowable design stress, the P in formula 2 must be the maximum load that will be applied to the spring, either at solid height, $P_s = R(L - H)$, or at maximum deflection (F). If neither the maximum deflection nor solid height are specified, assume that P_s is equal to 1.25 times the maximum specified load.

If the tensile strength of the estimated wire size is slightly larger than the tensile strength used for the trial value of stress, the estimated wire size (d) may temporarily be assumed as an acceptable value of d. However, if the two values of tensile strength are far apart, the calculated d is used in turn to determine an approximate value of D from D = OD − d and an approximate value of stress from the appropriate tables on pages 44 to 46 adjusted by the percentages from Table I on pages 41 and 42. These new trial values are substituted into formula 2 to calculate a revised wire diameter (d). If this value of d is quite close to the first, it can be assumed acceptable and the next larger standard wire size selected. If not, it is necessary to repeat the calculation in formula 2 once again.

With the acceptable value of d, the number of active coils (n_a) are calculated from formula 1 for rate (R). Solid height (H) is then determined from the appropriate formula given for the total coils (N_t) and wire diameter (d) (Table 1, p. 14) to verify that space limitations are being met.

Stress

Stress at solid height (S_s) and stress at load 1 (S_1) are then calculated in formula 2, using P_s and P_1, respectively.

The Wahl curvature-stress correction factor (K) is determined from the formula given (page 8) with C = D/d, and corrected values (S_{sk} and S_{1k}) of S_s and S_1 are then calculated. These figures are compared to the maximum allowable design stress, which is a product of tensile strength of the wire (S_t) for the accepted diameter and the appropriate percentages on pages 41 and 42. Time may be saved in design by first calculating S_{sk} alone and then S_{1k} only if S_{sk} is found to be too high. Comparison of corrected stress with maximum allowable stress indicates one of three conditions:

1. **S_{1k} and S_{sk} both below the maximum allowable.**—Stress is acceptable and the spring will not set in application. If S_{sk} is quite far below the maximum, it is likely to be a somewhat inefficient design. It might then be worthwhile to recalculate using a smaller wire diameter, a smaller coil diameter, and/or fewer active coils.
2. **S_{1k} below S_{sk} above the maximum allowable.**—The spring will not set at L_1, but will do so at some larger deflection between L_1 and solid height. If the spring is likely to be deflected beyond L_1 in use or assembly, n_a should be increased (or even D if space can be made available) along with a corresponding increase in wire size to reduce stress. Otherwise, this spring can be preset. If deflection will never exceed L_1, the original design may be acceptable.
3. **Both S_{1k} and S_{sk} above the maximum allowable.**—The spring is highly stressed and will set before it reaches the specified load (P_1). Although it is sometimes possible by presetting to achieve acceptable values of S_{1k} and S_{sk}, the most common solution is to reduce the stress by increasing the amount of wire in the spring. Presetting is only an option when the maximum stress (S_{sk}) is less than 60 percent of the tensile strength. Increasing n_a and D results in a larger d in formula 1 and then a smaller S in formula 2. This approach is limited both by maximum available space and by the fact that H must be less than L_1.

While the actual step-by-step procedure depends on the particular needs of the design problem, the basic method described above is used in designing most common compression springs. The specifications are somewhat different for springs in which the user is interested primarily in load per unit deflection. Designers usually specify rate (R) and rate tolerance, free length (L), solid height (H), and any space limitations. The only difference in procedure, however, is to calculate the maximum load (P_{max}) as $P_{max} = R(L - H)$ and use this value in formula 2.

Design Examples

EXAMPLE 1

Design a compression spring to meet the following requirements: O.D. = 0.925 in. (23.50 mm), free length L = 1.713 in. (43.51 mm), load $P_1 = 50 \pm 5$ lb. (222.4 ± 22.2N) at $L_1 = 1.278$ in. (32.46 mm), ends closed and ground, maximum solid height H = 1.060 in. (26.92 mm). The material is oil-tempered wire.

Rate

The required spring rate (R) is determined in

$R = P/F = 50/(1.713 - 1.278) = 115$ lb/in. (20.14 N/mm)

and the approximate load at solid height (P_s) is

$P_s = R(L - H) = (115)(1.713 - 1.060) = 75.1$ lb. (334N).

Wire Diameter

In this case, assume a trial mean diameter 0.100 in. (2.54 mm) less than the nominal O.D. and a trial design stress of 0.45 (200,000) = 90,000 psi (621 MPa) where S_t = 200,000 psi (1379 MPa) is in the high-diameter range for oil-tempered wire. Transpose the stress formula 2 and solve for a trial wire diameter.

$$d = \sqrt[3]{\frac{8PD}{\pi S}} = \sqrt[3]{\frac{8(75.1)(0.825)}{\pi(90{,}000)}} = 0.121 \text{ in. } (3.07 \text{ mm})$$

(suggest using 0.125)

S_t = 220,000 psi (1517 MPa) for d = 0.125 in. (3.18 mm); since this is only 10 percent over the assumed S_t = 200,000 (1379 MPa) there is no need to recalculate d in formula 2. Using the 0.125 in. (3.18 mm) temporarily as the acceptable d, solve for D = O.D. − d = 0.925 − 0.125 = 0.800 in. (20.32 mm)

Number of Active Coils

Solve for n_a by transposing the spring rate formula 1.

$$n = \frac{Gd^4}{8RD^3} = \frac{(11.5 \times 10^6)(0.125)^4}{8(115)(0.800)^3} = 5.96 \text{ (use 6) coils}$$

Solid Height

With closed and ground ends, solid height (H) is determined in

$H = d(n_a + 2) = 0.125(6 + 2) = 1.00$ in. (25.40 mm)

Because this solid height is smaller than the 1.060 in. (26.92 mm) specified, d = 0.125 in. (3.18 mm) can be accepted with regard to this space limitation.

Stress

Calculate the uncorrected stress for solid compression in

$$S_s = \frac{8PD}{\pi d^3} = \frac{8(75.1)(0.800)}{\pi(0.125)^3} = 78{,}300 \text{ psi (540 MPa) (uncorrected)}$$

The Wahl correction factor (K) is calculated from:

$$K = \frac{(4c-1)}{(4c-4)} + \frac{0.615}{C} = \frac{[(4)(6.4)-1]}{[(4)(6.4)-4]} + \frac{0.615}{6.4} = 1.23$$

Where: C = D/d = 0.800/0.125 = 6.4

The corrected stress at solid is:

$S_{sk} = KS_s = (1.23)(78{,}300) = 96{,}300$ psi (664 MPa)

The maximum allowable design stress is 0.45 (220,000) = 99,000 psi (683 MPa), so that stress will be safe for the application.

EXAMPLE 2

Design a compression spring with closed ends to support a plunger which slides in a 0.203 in. (5.16 mm) hole. Type 302 stainless steel is needed because of the marine environment in the end use. The minimum length between the end of the plunger and the bottom of the hole is 0.340 in. (8.64 mm). The length of the spring at its normal position is 0.385 in. (9.78 mm), and it is never compressed further in either application or assembly. A trial spring of 0.035 in. (0.89 mm) music wire which operated satisfactorily exerted 7.2 lb. (32 N) at its normal position and was 0.475 in. (12.07 mm) long when free.

Rate

The spring rate is

$R = P/F = 7.2/(0.475 - 0.385) = 80$ lb./in. (14.0 N/mm)

Mean Diameter

Allowing 0.015 in. (0.38 mm.) for coil diameter tolerance (Table 2 in Tolerances section) and coil expansion due to deflection, the O.D. is then 0.188 in. (4.78 mm), and D = O.D. − d = 0.188 − 0.035 = 0.153 in. (3.89 mm).

Number of Active Coils

Assuming the same wire diameter of 0.035 in. as in the trial spring, using $G = 10 \times 10^6$ psi (69×10^3 MPa) for Type 302 stainless steel, solve for the number of active coils (n_a) in

$$n_a = \frac{Gd^4}{8RD^3} = \frac{(10 \times 10^6)(0.035)^4}{8(80)(0.153)^3} = 6.5 \text{ coils}$$

Solid Height

N_t = 8.5 total coils for a closed end spring and solid height (H) is

$H = d(N_t + 1) = 0.035(8.5 + 1) = 0.333$ in. (8.46 mm)

This allows clearance since 0.340 (8.64 mm) is maximum space available.

Stress

Calculate the uncorrected stress at the normal assembly position in

$$S_1 = \frac{8PD}{\pi d^3} = \frac{8(7.2)(0.153)}{\pi(0.035)^3} = 65{,}400 \text{ psi (uncorrected) (451 MPa)}$$

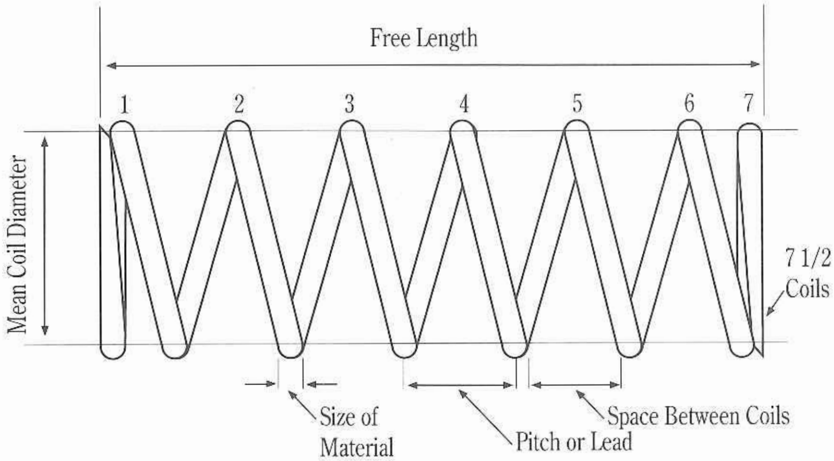
and the corrected stress is determined for C = D/d = 0.153/0.035 = 4.4 using the Wahl correction formula, page 8.

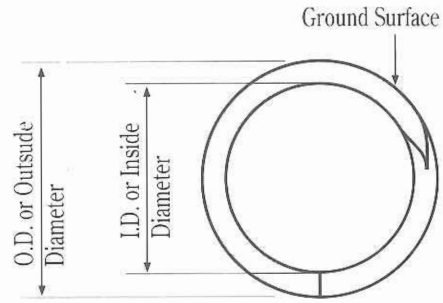
$$K = \frac{4(4.4)-1}{4(4.4)-4} + \frac{0.615}{4.4} = 1.36$$

$S_{1k} = 1.36(66{,}000) = 90{,}000$ psi (621 MPa)

Maximum allowable design stress is 0.35(274,000) = 95,900 psi (661 MPa). The stress at normal position is then acceptable. But if the spring were compressed much below normal position, it probably would lose load since it appears that S_{sk} would exceed maximum allowable.

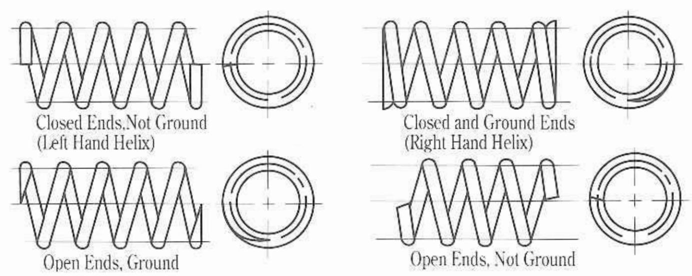
Compression Springs—Specification Form





Mandatory Specifications
(fill in only those required)

1. OUTSIDE DIAMETER
   a. ___ in. (mm) max. or
   b. ___ in. (mm) ± ___ in. (mm)
2. INSIDE DIAMETER
   a. ___ in. (mm) min. or
   b. ___ in. (mm) ± ___ in. (mm)
3. Load ___ lb. (N) ± ___ lb. (N) @ ___ in. (mm)
   Load ___ lb. (N) ± ___ lb. (N) @ ___ in. (mm)
   Rate ___ lb./in. (N/mm) ± ___ lb./in. (N/mm)
   between lengths of ___ in. (mm) and ___ in. (mm).
4. Maximum solid height ___ in.(mm)
5. Direction of helix (L, R or optional) ___
6. Type of ends ___



Advisory Data

1. FREE LENGTH
   a. ___ in. (mm) max., ___ in. (mm) min. or
   b. ___ in. (mm) ± ___ in. (mm)
2. Wire diameter ___ in. (mm)
3. Mean coil diameter ___ in.(mm)
4. No. of active coils ___
5. Total no. of coils ___

Special Information

1. Type of material ___
2. Finish ___
3. Squareness (free): within ___°
4. Frequency of compression, ___ cycles/sec, and working range, ___ in. (mm) to ___ in. (mm) of length.
5. Operating temp. ___ °F (°C)
6. End use or application ___
7. Other ___